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The effect of ultrasonic processing on solidification microstructure and heat transfer in stainless steel melt

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ABSTRACT

The heat transfer in the ultrasonic processing of stainless steel melt is studied in this thesis. The temperature field is simulated when the metal melt is treated with and without ultrasound. In order to avoid the erosion of high temperature melt, ultrasound was introduced from the bottom of melt. It is found that the temperature of melt apparently increases when processed with ultrasound, and the greater the ultrasonic power is, the higher the melt temperature will be; ultrasonic processing can reduce the temperature gradient, leading to more uniform temperature distribution in the melt. The solidification speed is obviously brought down due to the introduction of ultrasound during solidification, with the increasing of ultrasonic power, the melt temperature rises and the solidification speed decreases; as without ultrasound, the interface of solid and mushy zone is arc-shaped, so is the interface of liquid and mushy zone, with ultrasound, the interface of solid and mushy zone is still arc-shaped, but the interface of liquid and mushy zone is almost flat. The simulation results of temperature field are verified in experiment, which also indicates that the dendrite growth direction is in accord with thermal flux direction. The effect of ultrasonic treatment, which improves with the increase of treating power, is in a limited area due to the attenuation of ultrasound.

1. Introduction

Ultrasonic treatment of metal melt is coming into more and more common use in the field of casting for its effect in refining grains and the avoidance of casting defects so as to improve the performance of metal materials [1–5]. Ultrasonic treatment is a kind of external-field processing, which contributes to the refinement of solidification microstructure mainly through ultrasonic cavitation and streaming [6–14]. The solidification microstructure is closely related to the heat transfer conditions during the melting and solidification, it is necessary to investigate the effect of ultrasonic treatment on heat transfer in the process of melting and solidification.

Substantive researches about the enhancement of heat transfer in the fluids under ultrasonic treatment have been carried out. Kave et al. [15] researched the effect of ultrasonic streaming on heat convection, and found its effect, named as "heat streaming", was much better than that of natural convection. Hyun et al. [16] studied the ultrasonic streaming in the air as well as its influence on heat transfer, and concluded that the heat transfer coefficient had a proportional increasing to streaming velocity. Riley et al. [17] found that the heat convection enhancement as a result of ultrasound introducing was especially obvious near the wall, the turbulence due to ultrasonic streaming promoted heat transfer as well. Park et al. [18] proposed that ultrasonic streaming could apparently shorten the melting time of paraffin, the reason was that the forced convection enhanced the melting heat transfer. Nomura et al. [19] investigated the effect of ultrasonic cavitation and streaming on heat transfer intensification in a narrow plane, and discovered that the micro-jet caused by cavitation significantly boosted the heat conduction.

Cai et al. [20] established the flow and heat transfer model, in which the impact of phase-change, bubble motion and incoagulable gas was considered, to investigate the natural heat convection with and without ultrasonic processing in water, they found that both the temperature uniformity and the heat transfer coefficient of the heating surface were obviously improved. The mechanism of heat transfer enhancement was that the jet released by collapsing bubbles promoted the mixing of fluid and decreased the thickness of heat boundary layer directly. Kim et al. [21] numerically simulated the heat transfer in water processed with ultrasound, the results revealed that ultrasound could greatly reduce the temperature gradient in the fluid and improve the heat convection coefficient of the heating surface. Yasui et al. [28] calculated the spatial distribution of the acoustic amplitude in a sonochemical reactor using the finite

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Nomenclature

a	thermal diffusivity
A	surface area
c	velocity of ultrasound
c_1	empirical constant
c_2	empirical constant
c_μ	empirical constant
c_l	liquid specific heat capacity
c_s	solid specific heat capacity
c_p	specific heat capacity
f	frequency of ultrasonic wave
g	gravitational acceleration
h	heat convection coefficient
h_0	sensible enthalpy
H	enthalpy
ΔH	latent heat content
k	turbulent kinetic energy
L	side of closed cavity
P	pressure
q	heat flux
q_v	inner heating source
Q	latent heat of the material
Q_c	convection heat transfer
Q_r	radiant heat transfer
Q_u	energy flux supplied by heating device
t	time
T	temperature
T_0	environment temperature
ΔT	temperature difference
v	flowing velocity
W	latent heat of fusion
S	source term
I_0	acoustic intensity

Greek symbols

ε	turbulence dissipation rate
λ	thermal conductivity
λ_l	liquid thermal conductivity
λ_s	solid thermal conductivity
μ	dynamic viscosity
μ_t	turbulence viscosity
ρ	density
σ	Stefen–Boltzman constant
σ_k	empirical constant
σ_ε	empirical constant
ξ	emissivity coefficient
α	heating effect
β	heat diffusivity coefficient
γ	liquid fraction

Subscripts

ref	reference value
solidus	solid phase value
liquidus	liquid phase value
eff	effective value
i	x axis direction
j	y axis direction
t	turbulent flow

element method (FEM), and the acoustic field in a sonochemical reactor was coupled with the vibration of the reactor's wall. The horizontal stripes of the pressure antinodes was reproduced when the attenuation coefficient of ultrasound was in 0.5–5 m^{-1}. The attenuation of ultrasound was partly due to the existence of cavitation bubbles. Klima et al. [32] studied the effect of sonoreactor geometry on the distribution of ultrasonic intensity, the calculation together with experiment revealed that the whole reactor behaved like a resonator and the energy distribution depends strongly on its shape. Legay et al. [33] designed a new kind of ultrasonically-assisted heat exchanger, it was demonstrated that ultrasound can be used efficiently as a heat transfer enhancement technique, even in such complex systems as heat exchangers.

The current research topic of ultrasound induced heat transfer enhancement is mainly focused on water, researches about heat transfer intensification in metal melts processed with ultrasound were rarely found, and most of the current researches are solely based on experiment or simulation. It was pointed out by Ohno [31] that the key factor affecting the solidification of alloys is the convection inside the melt. We paid close attention to the effect of natural convection and forced convection on the solidification when treated with and without ultrasound, respectively. In this article, we established the flow and heat transfer model in the melting and solidification procedure of 304 stainless steel melt under ultrasonic treatment, to investigate the influence of ultrasonic processing on heat transfer during melting and solidification, the simulation results were verified by experiments, the effect of ultrasonic treatment on solidification microstructure is discussed as well.

2. Simulation

In this experiment, the metal to be treated was processed as an unit piece with the booster, which was placed upward vertically, and the metal was melt by induction coils. After that, ultrasonic vibration was introduced into the melt from its bottom. The diameter of the treated metal was 26 mm, the height was 30 mm, the power of the ultrasound device was adjustable in the range of 0–300 W. The schematic of experimental setup and meshes used in simulation is shown in Fig. 1.

The ultrasound generator, the metal processing system, and the stainless steel samples treated in experiment are shown in Fig. 2. A through quartz tube with wall thickness of 3 mm were fastened on the probe side wall by insulated felt. The tube functioned as a shield to prevent the dripping of the melt, but it was not tightly jointed with the probe, thus, the effect of the tube vibration was neglected.

A plane section crossing the central axis of the cylinder is chosen to study, and the xOy coordinate system is established as following to analyze the simulation results.

As it was pointed out in [25], the threshold of ultrasonic cavitation in steel melt is much higher than that in water. Moreover, the existence of cavitation core is the prerequisite for ultrasonic cavitation. Generally speaking, the cavitation core in liquid is the small amount of air dissolved in it. It is an important step to degass the steel melt in industry application, as the dissolved gas (oxygen, nitrogen and so on) could badly influence the quality of steel melt during the refining process. After degassing, it is considered that there are almost no cavitation cores in the melt, so, the effect of ultrasonic cavitation was not included in the calculation.

The only heat transfer in the metal during melting process without ultrasound introduction is natural convection, the melt was considered as the fluid according with Boussinesq model [22], in which the density of fluid was set to be a constant, the equation of Boussinesq approximation [22] is as follows:

$$(\rho_1 - \rho_0)g \approx -\rho_0\beta(T_1 - T_0)g \tag{1}$$